The Spatial Layout and Vulnerability Analysis of the High-speed Rail Network

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Abstract: This study focuses on the spatial organization patterns and vulnerabilities of the high-speed rail network in the three northeastern provinces of China (Liaoning, Jilin, and Heilongjiang). The Northeast region, with its unique political and historical background and relatively independent geographical location, has a relatively complete and developed railway network, especially characterized by a high density of conventional rail lines. In recent years, with the rapid development of high-speed rail, an increasing number of cities in the three northeastern provinces have been integrated into the high-speed rail network, leading to significant changes in the intercity connectivity network.
***Keywords*:** high-speed railway network, complex network, vulnerability

1. Introduction

In China, research on the spatial organization of high-speed rail (HSR) networks has deepened in tandem with the rapid development of HSR construction[1]. In the early stages, scholars primarily focused on the impacts of HSR networks on individual cities or regions, such as the improvement of urban accessibility, the flow of economic factors, and the reshaping of spatial structures[2-3]. As the HSR network has continued to improve, research has gradually shifted to a more macroscopic scale, exploring the influence of HSR networks on the national economic pattern, urban agglomeration development, and regional integration[3-4].

Research on the spatial organization of HSR networks in foreign countries started earlier and has a relatively mature theoretical system[5-6]. The content of these studies not only includes the impact of HSR networks on individual cities or regions but also examines the role of HSR networks in global economic integration, transnational investment, and international trade. Foreign scholars have also compared the HSR networks of different countries to explore the commonalities and differences in HSR network development.

In terms of research methods, domestic scholars have employed various approaches such as the Analytic Hierarchy Process (AHP), Fuzzy Comprehensive Evaluation, and Network Analysis to quantitatively assess the vulnerability of transportation systems[7]. Additionally, they have conducted empirical analyses of transportation system vulnerability based on specific cases, such as extreme weather events and terrorist attacks[8-9]. These studies have provided valuable suggestions and measures for enhancing the resilience and security of transportation systems. Foreign scholars, on the other hand, have utilized advanced methods and technical means such as scenario simulation and System Dynamics models to comprehensively and deeply assess the vulnerability of transportation systems.

2. Characteristics of High-Speed Rail Network Spatial Layout

2.1 Spatial Distribution

The high-speed rail (HSR) network in the three northeastern provinces (Liaoning, Jilin, and Heilongjiang) has taken preliminary shape. The Harbin-Dalian (Hada), Changchun-Baishan-Ulanhot (Changbai-Ulanhot) HSR lines, which run vertically through the three northeastern provinces and horizontally across Jilin and Inner Mongolia, together with the Harbin-Qiqihar (Haqi), Changchun-Hunchun (Changhun), Panjin-Yingkou (Panying), Shenyang-Dandong (Shendan), and Dandong-Dalian (Dandalian) HSR lines that connect major urban clusters such as Harbin-Daqing-Qiqihar (Hadaqi), central Jilin, and central-southern Liaoning, form the HSR network of the three northeastern provinces. These HSR lines are mainly distributed in the major cities and regions of Liaoning, Jilin, and Heilongjiang provinces, creating a relatively comprehensive HSR transportation system.

2.2 Classification of Node Cities

The classification of node cities in the HSR network of the three northeastern provinces can be based on factors such as HSR accessibility, the number of connecting lines, and daily HSR frequencies. The following is a general classification:

(1) Core Node Cities: Shenyang, Changchun, and Harbin. These cities are the political, economic, and cultural centers of the three northeastern provinces. They have high HSR accessibility, numerous connecting lines, and high daily HSR frequencies, making them the core nodes of the HSR network in the region.

(2) Secondary Node Cities: Dalian, Jilin, and Qiqihar, among others. These cities hold important positions in the HSR network of the three northeastern provinces, connecting multiple major cities and regions with relatively high daily HSR frequencies. They are significant nodes within the HSR network.

(3) General Node Cities: Cities such as Anshan, Fushun, Benxi, Dandong, Jinzhou, Yingkou, Songyuan, Siping, and Yanji. Although these cities have relatively lower HSR accessibility, they still play important roles in regional transportation and economy, serving as general nodes in the HSR network.

2.3 Line Connectivity

The HSR network in the three northeastern provinces has good line connectivity, forming a relatively comprehensive HSR transportation system. Major HSR lines such as Hada, Changbai-Ulanhot, Haqi, Changhun, Panying, Shendan, and Dandalian not only connect the main cities and regions of the three northeastern provinces but also form several HSR hubs, such as Shenyang South Station, Changchun West Station, and Harbin West Station. These hub stations, with their high connectivity and accessibility, are equipped with comprehensive transportation facilities and services, providing passengers with convenient and comfortable travel experiences.

Moreover, the HSR network in the three northeastern provinces emphasizes integration with other modes of transportation, such as highways and civil aviation, forming a comprehensive transportation system. This integration not only enhances the accessibility and convenience of the HSR network but also promotes coordinated development among different transportation modes.

2.4 Comparison with Domestic and International HSR Networks

Compared with other domestic and international HSR networks, the HSR network in the three northeastern provinces has the following characteristics:

Network Density: The HSR network density in the three northeastern provinces is relatively high, especially in Liaoning Province, where HSR lines are densely distributed, forming a comprehensive HSR transportation system.

Node City Classification: The classification of node cities in the HSR network of the three northeastern provinces is relatively clear, with distinct hierarchies among core node cities, secondary node cities, and general node cities.

Line Connectivity: The HSR network in the three northeastern provinces has good line connectivity, forming multiple HSR hubs and transportation nodes that provide convenient and comfortable travel experiences for passengers.

In summary, the HSR network in the three northeastern provinces exhibits relatively comprehensive characteristics in its spatial layout, with high accessibility and convenience. In the future, with the continuous advancement and improvement of HSR construction, the HSR network in the three northeastern provinces will better serve regional economic and social development.

3. Vulnerability Research of High-Speed Rail Networks

3.1 Topological Structure Vulnerability

3.1.1 Importance of Nodes and Lines

In high-speed rail (HSR) networks, the significance of nodes (such as stations) and lines is self-evident. The failure of a single node can lead to a decline in the connectivity of the entire network, and may even cause partial or complete paralysis. For example, the failure of nodes with high degree values (i.e., stations with multiple connecting lines) has a more pronounced impact on the network. In the Northeast HSR network, stations in core cities such as Harbin, Shenyang, and Dalian have high degree values. The failure of these stations would significantly affect the operation of the entire HSR network.

3.1.2 Network Connectivity:

Network connectivity is one of the important indicators for measuring the vulnerability of HSR networks. When certain nodes or lines in the network fail, connectivity is compromised, leading to transportation disruptions between some regions. By calculating parameters such as the average path length and network diameter, the connectivity of the HSR network can be assessed. Changes in these parameters can reflect the network's vulnerability when subjected to attacks or failures.

3.1.3 Network Efficiency and Resilience:

Network efficiency is an important indicator of the operational efficiency of HSR networks, reflecting the connection efficiency between nodes and the speed of information transfer within the network. Resilience, on the other hand, refers to the network's ability to recover after being subjected to attacks or failures. A resilient network can return to normal operation in a short time, minimizing the impact on socio-economic activities. The Northeast HSR network has seen rapid development in recent years, with improved network efficiency, but resilience still needs to be enhanced.

3.2 Operational Environment Vulnerability

(1) Natural Environmental Factors.

The Northeast region has relatively unstable geographical conditions and potential climatic hazards. For example, extreme weather conditions such as heavy rainfall, typhoons, and blizzards can damage HSR lines and station facilities, affecting the normal operation of high-speed trains. In addition, geological disasters such as landslides and mudflows also pose threats to the HSR network.

(2) Public Health Events.

The medical and health conditions in the Northeast region are relatively weak. In the event of a major public health emergency (such as the COVID-19 pandemic), the operation of the HSR network would be significantly impacted. The outbreak of public health events may lead to crowded stations and restricted passenger movement, thereby affecting the connectivity and operational efficiency of the HSR network.

3.3 Management Subsystem Vulnerability

(1) Emergency Rescue Management System.

The completeness of the emergency rescue management system for HSR networks directly affects the network's resilience. Currently, the emergency rescue management system of the Northeast HSR network still has some shortcomings, such as uneven distribution of rescue resources and slow response times.

(2) Market-Oriented Demands and Operational Pressure.

With the advancement of railway marketization, HSR networks face greater operational pressure. To meet market demands and improve operational efficiency, HSR networks may need to continuously optimize and adjust their schedules. However, such optimization and adjustments can also bring certain risks. For example, frequent changes in schedules may cause inconvenience for passengers and destabilize network operations.

4. Comprehensive Evaluation and Response Strategies

(1) Comprehensive Evaluation.

The vulnerability of the Northeast HSR network is a complex issue that requires a comprehensive evaluation from multiple perspectives. By considering factors from various aspects, including topological structure, operational environment, and management subsystems, a more holistic understanding of the HSR network's vulnerability can be achieved.

(2) Response Strategies.

To address the vulnerability of the Northeast HSR network, the following strategies can be adopted: Enhance the protection and monitoring of network nodes to improve their reliability and resilience.Optimize the network structure to increase connectivity and operational efficiency.Strengthen the monitoring and early warning mechanisms for natural disasters and public health events to enhance the ability to respond to emergencies.Improve the emergency rescue management system to increase response speed and efficiency.Balance market-oriented demands with operational pressures to ensure the stable operation of the HSR network.

5. Conclusion

In summary, the study of the vulnerability of the Northeast HSR network is a complex and important topic. By considering factors from multiple aspects, a more comprehensive understanding of the HSR network's vulnerability can be achieved, and corresponding response strategies can be implemented to reduce its vulnerability and enhance the stability and reliability of the HSR network.

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